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# Geodetic imaging of thermal deformation in geothermal reservoirs - production, depletion and fault reactivation

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ABSTRACT

We investigate thermally induced surface deformation in geothermal systems. To define source mechanisms at depth, we assess the mechanical process of subsurface deformation by assuming a spherically cooled fractured reservoir in an infinite medium and derive relations that define magnitudes of thermal contraction, stress change and permeability evolution. The magnitude of thermal deformation in typical geothermal system is larger than anticipated and suggests two different modalities of surface subsidence – thermal contraction and fault reactivation. Here, surface deformation (vertical displacement, surface tilt and horizontal strain) induced by the two different modalities are assessed with Mogi (contraction) and Okada (slip) models and compared with instrumental sensitivity of high precision surface geodetic tools. We show that 1 year of geothermal operation at 10 MW with a power plant conversion efficiency of 12% can yield ~$3.0 \times 10^4$ $m^3$ of subsurface volume change. For a reservoir at 2000 m depth, this induces ~1.7 mm of vertical surface displacement, ~800 nano-radians of surface tilt and ~900 nano-strains of surface strain. This result implies that typically observed magnitudes of surface subsidence (order of cm/year) are naturally expected in massive (100 MW scale) geothermal operations and observed surface subsidence may largely be the result of thermal contraction. Conversely, thermal unloading can trigger fault reactivation. Analysis with an Okada slip model shows these shear offsets on pre-existing faults can also result in surface deformations of considerable magnitude. Our analysis of field operational data from various geothermal projects suggests that both thermal contraction and slow fault reactivation may contribute to the observed large surface deformation. Comparison of predicted deformation with instrumental sensitivity of high precision surface tools confirms that geodetic signals, especially tilt and strain, are indeed sufficiently large to describe reservoir evolution and to potentially deconvolve reservoir parameters of interest, such as permeability.

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## 1. Introduction

Surface deformations of significant magnitude in a number of geothermal fields have been observed by both interferometric methods (InSAR) (Ali et al., 2016; Eneva et al., 2012; Falorni et al., 2011; Fialko and Simons, 2000; Foxall and Vasco, 2003; Vasco et al., 2002b; Vasco et al., 2013) and by direct measurement of surface tilt (Vasco et al., 2002a). Subsurface deformation induced by cold water injection generally conforms to two different modalities: (i) isotropic volume change and (ii) injection induced shear offset on finite faults. Isotropic volume change can be induced by either thermal contraction (volume decrease) or pressure dilation (volume increase) in the reservoir with shear slip similarly resulting from changes in effective stress induced by changes in fluid pressures or temperature. Ali et al. (2016) recently show that surface subsidence in the Brady Hot Springs geothermal field may result from the contraction of shallow strata similar to the potential for pressure driven early-time slip and temperature driven late-time slip postulated to result in geothermal reservoirs (Gan and Elsworth, 2014).

Although surface deformation in geothermal systems can be induced by both pressure and temperature change, observations suggest that it may be mainly temperature driven since the deformations are slow and continuous – similar to the progress of conduction-limited heat transport. Surface subsidence rates are typically several cm/year and continuous through geothermal operations. As discussed by Gan and Elsworth (2014), temperature driven stress change is slow and continues until the reservoir is thermally depleted. Conversely, pressure change is concentrated early during fluid injection, limited by boundaries (well bore pressures) and typically localized near-wellbore regions of injection or production, where effects are most focused.

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Linking the observed deformation with a subsurface mechanism helps define active processes during reservoir evolution. Such models may be used to constrain magnitudes of heat energy transfer from rock to fluid and the evolution of transport characteristics of the reservoir. The detection of slip processes on finite faults in turn constrains fluid flow and the evolution of major flow paths, and may allow the precursors to injection-induced seismicity to be defined and monitored.

State of the art instruments that measure strain and tilt provide extremely high sensitivity and resolution of surface deformation. The Gladwin tensor strainmeter (GTSM) provides a precision of <1 nano-strain in the short term (Gladwin, 1984) and current commercial tilt meters (Pinnacle Denali tiltmeter) have a sensitivity ~1 nano-radian (Wright et al., 1998). We will demonstrate below that these instruments have sensitivities (in this study, 1 nano-radian and 1 nano-strain) that are sufficiently fine to describe reservoir thermal processes, and thus will provide valuable information on reservoir evolution and improve geothermal development practices in the field.

Below, we first assess mechanisms of thermally-driven contraction, stress change and permeability evolution of a fractured reservoir within an elastic half-space. This then defines the magnitudes of the signal, considering the coupling and decoupling processes between the reservoir and the surrounding rock. We then define the expected surface deformation induced by both thermal contraction and field scale fault reactivation using the Mogi volumetric model (Mogi, 1958) and the Okada shear slip model (Okada, 1985). These are then compared with instrumental resolutions of current geodetic methods. Further, we analyze existing surface deformation data using these models to deconvolve processes within deep reservoirs.

## 2. Surface deformation

We assess surface deformation developed by two modes of subsurface deformations: (i) volume change due to thermal contraction and (ii) shear deformation due to slip on a finite fault plane. We apply the Mogi (1958) solution to analyze volume change and the Okada (1985) solution for shear deformation offset at depth to estimate the magnitude of maximum deformations: vertical displacement, surface tilt and strain.

### 2.1. Volume change

Volumetric strain, $\varepsilon_v$, induced by temperature change of unconstrained media is

$$\varepsilon_v = \alpha_v \Delta T \tag{1}$$

where, $\alpha_v$ is volumetric thermal expansion coefficient and $\Delta T$ is temperature change. Experimental data indicate that the volumetric thermal expansion coefficient of igneous rock is generally within the range $2 \times 10^{-5}$–$7 \times 10^{-5}$ within the temperature range between 30 °C and 400 °C (Cooper and Simmons, 1977). The magnitude of the thermal expansion coefficient suggests that thermal stresses can surpass poroelastic stresses in general geothermal system after sufficient duration of injection/recovery. For example, a temperature change of 100 °C with $\alpha_v = 5 \times 10^{-5}$ induces a volumetric strain of 0.005 while a 20 MPa change in pressure with a bulk modulus of 20 GPa induces only a volumetric strain of 0.001 in an unconfined system.

#### 2.1.1. Coupled deformation

Eq. (1) assumes strain under invariant stress. The presence of the surrounding rock, however, reduces the magnitude of deformation. The deformation reduction for elastically confined deformation of the ellipsoidal inclusion in an infinite elastic medium is solved analytically by Eshelby (1957). In the solution, volumetric strain of the unconstrained body $\varepsilon^*$ is defined by the relation

$$\varepsilon^c{}_{ij} = S_{ijkl} \varepsilon^*{}_{kl} \tag{2}$$

where $\varepsilon^c$ is the strain in the confined inclusion and $S_{ijkl}$ is the Eshelby tensor that is dependent on the shape of the inclusion. The relation can be directly applied to the constrained thermal contraction by substituting $\varepsilon^*{}_{ii} = 1/3\alpha_v \Delta T$ and $\varepsilon^*{}_{ij} = \varepsilon^*{}_{jk} = \varepsilon^*{}_{ki} = 0$. The Eshelby solution is derived by removing, then deforming and re-emplacing the ellipsoidal inclusion. Using a similar approach, we analyze a spherical fractured reservoir that has a modulus different from that of the surrounding rock (spherical soft inclusion) by assuming that all heat sources come from this localized volume. The Young's modulus of the fractured reservoir can be expressed as (Goodman, 1980),

$$\frac{1}{E_{res}} = \frac{1}{E} + \frac{1}{k_n S} \tag{3}$$

where, $k_n$ is normal stiffness of an individual fracture and $S$ is fracture spacing and $E$ is intact rock's Young's modulus. Accordingly, the fractured rock will generally be less stiff than the intact rock.

Fig. 1 illustrates deformations due to pressure change within (i) a spherical reservoir under zero stress, (ii) a spherical cavity in an infinite medium and (iii) their coupled behavior. We assume that the modulus of host and reservoir are different but that each are uniform and homogeneous. The magnitude of the coupled strain can be recovered as follows. Volumetric strain induced by pressure change in the unconstrained sphere (reservoir) with bulk modulus $K_{res}$ (Fig. 1 (a)) is

$$\varepsilon_{v,sphere} = \frac{\Delta P_{sphere}}{K_{res}} \tag{4}$$

For a spherical cavity in a matrix with shear modulus $G$, radial displacement ($u_r$) at the cavity boundary $r$ with an internal pressure change $\Delta P$, the deformation is $u_r = \Delta P \cdot r/4G$ [Yu and Houlsby, 1991]. Using this, volumetric strain induced by the pressure change in the spherical cavity in an infinite body (host rock) with shear modulus $G_{host}$ (Fig. 1 (b)) can be calculated as,

$$\varepsilon_{v,cavity} = \frac{\Delta P_{cavity}}{\frac{4G_{host}}{3}} \tag{5}$$

Note that the modulus of the reservoir ($K_{res}$) and the host rock ($G_{host}$) are different, but each medium is assumed to be a uniform elastic material. If the sphere is embedded in the cavity and both sphere and cavity deform together with the same pressure change in the sphere, then the deformations of both sphere and cavity will be the same, with the same volumetric strain (boundary displacements linked) as,

$$\varepsilon_v = \varepsilon_{v,sphere} = \varepsilon_{v,cavity} \tag{6}$$

and the total pressure change used to deform both sphere and cavity is the sum of the applied pressures that induces the strain in both sphere and cavity,

$$\Delta P = \Delta P_{sphere} + \Delta P_{cavity} \tag{7}$$

Eqs. (4), (5), (6) and (7) yield volumetric strain of coupled deformation as (Fig. 1 (c)),

$$\varepsilon_v = \frac{\Delta P}{K_{res} + \frac{4G_{host}}{3}} \tag{8}$$

The equivalent pressure due to the thermal stress can be calculated by equating Eqs. (1) and (4),

$$\Delta P = K_{res} \alpha_v \Delta T \tag{9}$$

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